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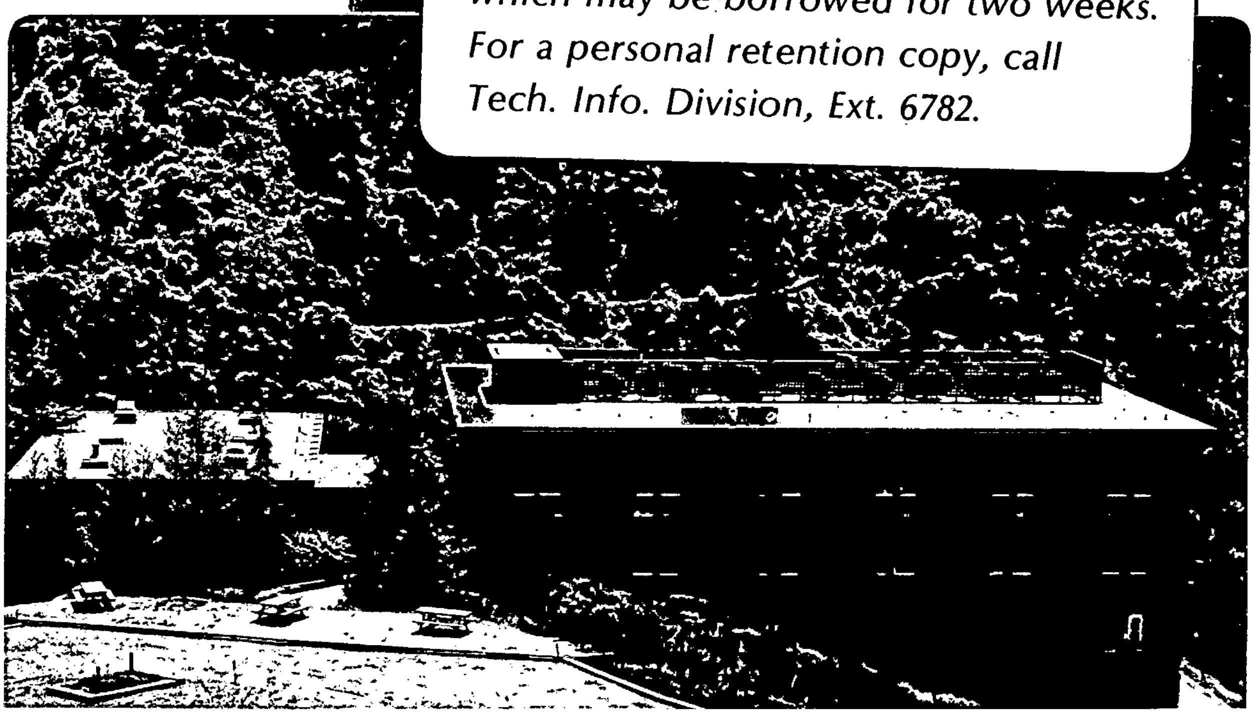

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H. Nayeb-Hashemi,* S. Suresh** and R. O. Ritchie**

*Department of Mechanical Engineering, Northeastern University, Boston, MA 02115

**Materials and Molecular Research Division, Lawrence Berkeley Laboratory and Department of Materials Science and Mineral Engineering, University of California, Berkeley, California 94720

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ON THE CONTRAST BETWEEN MODE I AND MODE III FATIGUE CRACK PROPAGATION UNDER VARIABLE AMPLITUDE LOADING CONDITIONS

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*Department of Mechanical Engineering, Northeastern University, Boston, MA 02115
**Department of Materials Science and Mineral Engineering, and Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

It is now well established that variable amplitude loading in the form of single spike or block overloads can result in pronounced transient retardations and even complete crack arrest during Mode I fatigue crack propagation. The origin of such effects has been ascribed to one or more of the following mechanisms: crack tip-yield zone interactions (1,2), crack tip blunting (3-5), branching (4-6), and crack closure due to residual plastic strains (7), fracture surface micro-roughness (4,5) and corrosion deposits (4,5).

Although the large majority of investigations to date have focussed on behavior under nominally Mode I (tensile opening) conditions, there has been recent interest in the behavior of fatigue cracks under Mode III (anti-plane shear) conditions, both for constant (8-12) and variable amplitude loading (12,13). The objective of the current note is to consider this latter case of Mode III fatigue cracks subjected to simple loading spectra in terms of the fractography of Mode III variable amplitude behavior and previously published crack growth rate results (13) and to compare such data with those well documented for Mode I cracks.

Based on cyclic torsion tests on circumferentially-notched cylindrical bars of an ASTM A469 rotor steel (yield strength 621 MPa) at zero mean torque (stress ratio R = -1), Nayeb-Hashemi *et al.* (13) report transient growth rate behavior for Mode III cracks following single overloads and high-low block loading sequences which is almost exactly opposite to that commonly observed under Mode I loading. For example, Figure 1 shows the behavior of Mode III and Mode I fatigue cracks subjected to single positive overloads. While the overload results in a *retardation* in Mode I growth rates, an initial *acceleration* is observed for Mode III cracks above a 50% overtorque.* Similarly, for single fully reversed overloads, Mode III cracks tend to *accelerate* on application of the larger cycle above a 50% overtorque (Fig. 2), again in complete contrast to Mode I where a *deceleration* occurs (14). In fact, the accelerating effect of the fully reversed overload is *larger* than the equivalent response of a single positive overload (c.f., Figs. 1a and 2), whereas under Mode I conditions fully reversed overloads generally show a *smaller* post-overload *retardation* than equivalent single positive overloads (14). Similar contrasting growth rate responses for Mode I and Mode III cracks are seen for high-low block loading sequences (13), as summarized in Table I.

The fractography associated with Mode III cracks subjected to fully reversed overloads is shown in Figure 3. Characteristic of torsional failures by macroscopic radial shear (8-13), fracture surfaces are flat and smeared with evidence of secondary (branch) cracking, especially for the larger overloads. In addition, there is clear evidence of pronounced

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*The terms overtorque and overtwist are defined as $(\Delta M_O - \Delta M_B)/\Delta M_B$ and $(\Delta\phi_O - \Delta\phi_B)/\Delta\phi_B$, respectively, where ΔM_O and $\Delta\phi_O$ are the torque and crack mouth rotation at the overload, and ΔM_B and $\Delta\phi_B$ are the corresponding baseline values (13).

Table I. Transient Growth Rate (dc/dN) Response of Mode I and Mode III Cracks Following Different Types of Variable Amplitude Loading Sequences

Load Sequence	Transient Crack Growth Rate Response	
	Mode I	Mode III
	$\frac{dc}{dN}$ decreases	$\frac{dc}{dN}$ increases
	above effect reduced	above effect enhanced
	$\frac{dc}{dN}$ slower*	$\frac{dc}{dN}$ faster*

*Compared to steady-state growth rate at lower load level.

rubbing and abrasion (i.e., sliding crack surface interference (9)), particularly at the point of application of the 100% and 250% overloads. The fractography of Mode I overloads (3-6), on the other hand, is generally characterized by a blunted and branched crack with severe signs of abrasion and often corresponding fretting oxide formation in the post-overload region (Fig. 4). Thus, although the growth rate response of Mode I and Mode III cracks to periodic overloads is entirely different, the mechanisms governing such response clearly involve crack branching and crack surface abrasion in both cases. Why then should Mode I cracks be retarded whereas Mode III cracks are accelerated?

In simple terms, one might expect periodic high amplitude cycles to always accelerate fatigue crack growth rates due to increased cyclic damage, in accordance with classical Miner's Rule concepts, i.e., each cycle results in the same amount of crack extension as if it were applied as a sequence of constant amplitude loads. This simple linear concept, however, is generally not observed for Mode I cracks subjected to broad band variable amplitude loading because loading sequence interaction effects (i.e., transient retardations, etc.) occur due to specific Mode I crack tip mechanisms. Recent experimental results obtained by Lankford and Davidson (6) and mechanistic models by Suresh (4,5) have shown that post-overload crack tip blunting, crack branching and crack closure due to fracture surface micro-roughness and fretting oxidation substantially reduce the effective driving force for crack extension, thereby retarding growth under Mode I loading conditions. The Mode III crack, conversely, is not subjected to blunting and can experience no fatigue crack closure since it is already in sliding contact, as evidenced by signs of crack surface interference on the Mode III fracture surfaces (Fig. 3). Thus, mechanistically, the local crack tip blunting and closure processes, which give rise to loading sequence interaction effects in Mode I cracks, would appear to have little relevance for Mode III cracks. Accordingly, as shown by the very limited variable amplitude Mode III crack growth data (13), anti-plane shear fatigue cracks simply accelerate when overloaded in accordance with Miner's Rule and apparently are not influenced by blunting and closure-induced loading sequence interaction effects. In fact, parametric modelling of variable amplitude Mode III crack growth behavior has shown that simple linear damage accumulation laws, such as Miner's Rule, are effective in predicting the post-overload response of Mode III cracks (13), whereas they would be inadequate for Mode I cracks.

Thus, from the perspective of defect-tolerant life prediction procedures, the Mode III fatigue crack subjected to variable amplitude loading presents a less complex problem than the Mode I crack. In the absence of loading sequence interaction effects, crack growth rates, and hence fatigue lifetimes, should be predictable from mere constant amplitude data simply by summing the damage (in the form of Coffin-Manson damage or in terms of the relevant crack tip characterizing parameter, i.e., ΔK, ΔCTD, etc.) for each load reversal in the loading history. Preliminary attempts at such simple modelling approaches for Mode III cracks subjected to single overload cycling and arbitrary loading histories in fact appear promising for the prediction of variable amplitude crack growth behavior (13,15,16).

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LIST OF FIGURE CAPTIONS

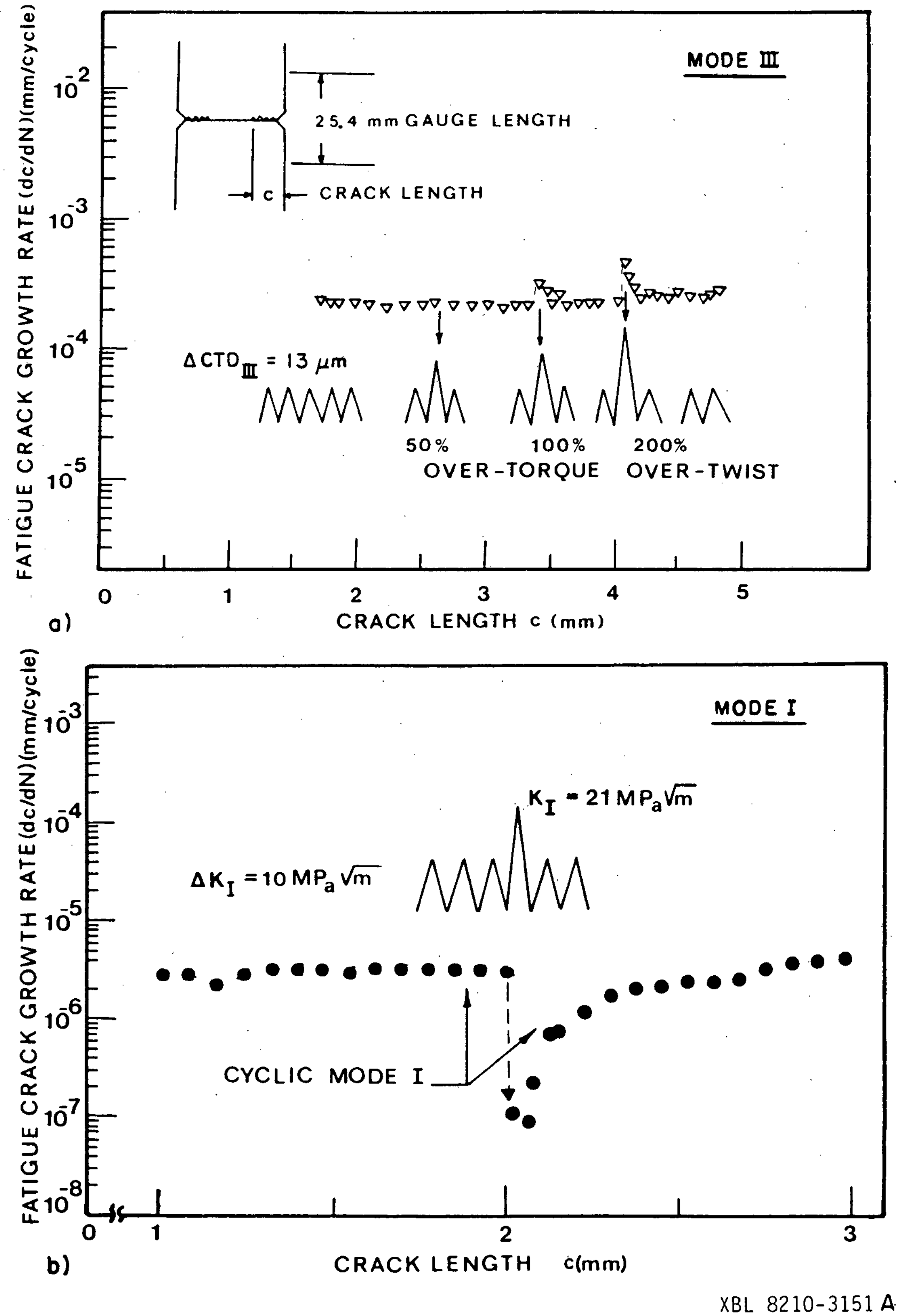

Fig. 1: Experimental fatigue crack growth rate (dc/dN) data in A469 rotor steel showing the differing transient response of a) Mode III and b) Mode I cracks to single positive overloads (13). Note the post-overload acceleration of Mode III cracks compared to the retardation of Mode I cracks.

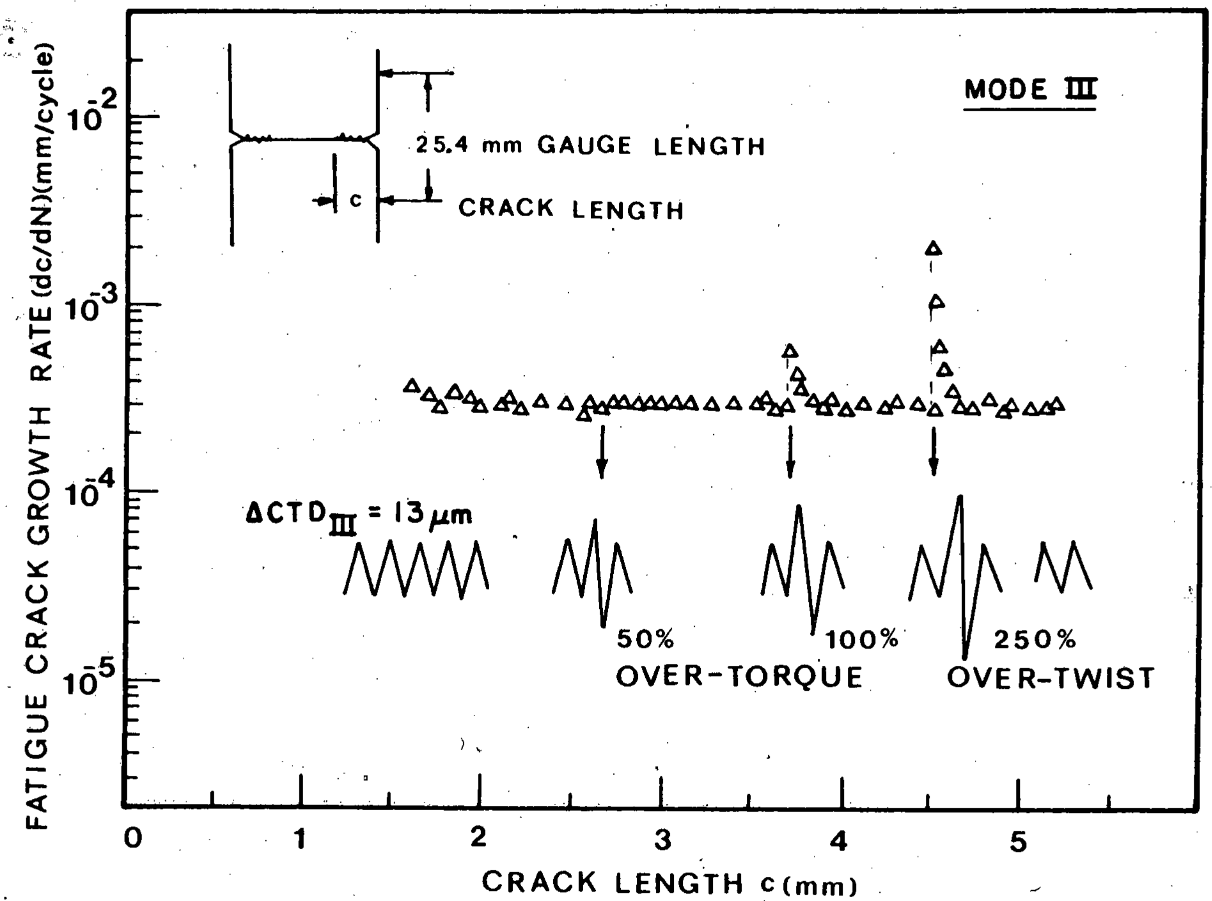

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Fig. 2: Experimental fatigue crack growth rate (dc/dN) data in A469 rotor steel showing the effect of 50, 100 and 250% fully reversed overloads on Mode III crack growth at baseline crack tip displacement (ΔCTD_{III}) of 13 μm (13). Note how the post-overload accelerations are larger than for the corresponding single positive overloads shown in Fig. 1a.

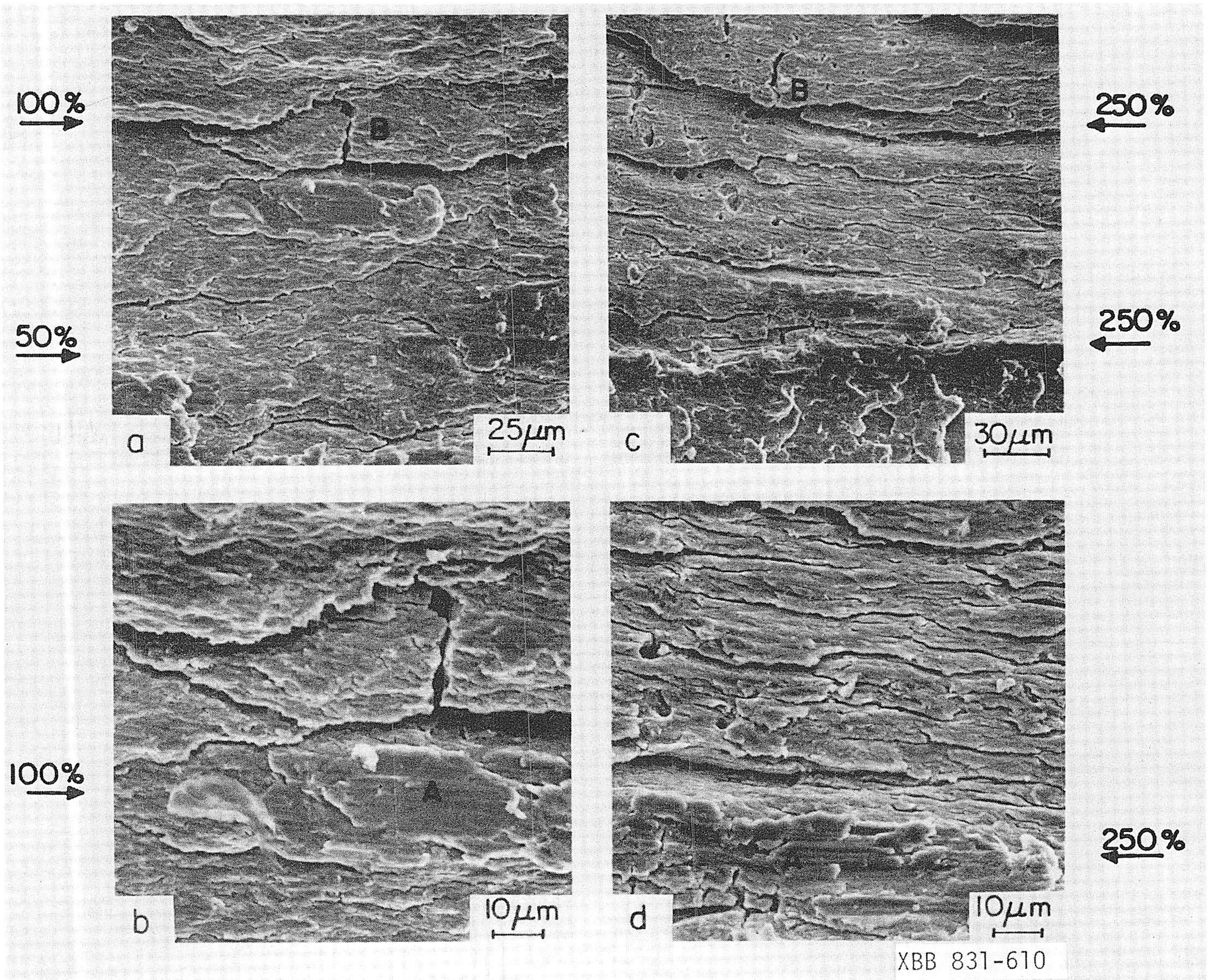

Fig. 3: Fractography of Mode III fatigue crack growth in A469 rotor steel corresponding to the 50, 100 and 250% fully reversed overloads shown in Fig. 2. Note how, at the onset of the overload cycles (marked by arrows), Mode III surfaces are characterized by more extensive fracture surface abrasion (A) and crack branching (B). General direction of crack growth is from bottom to top.

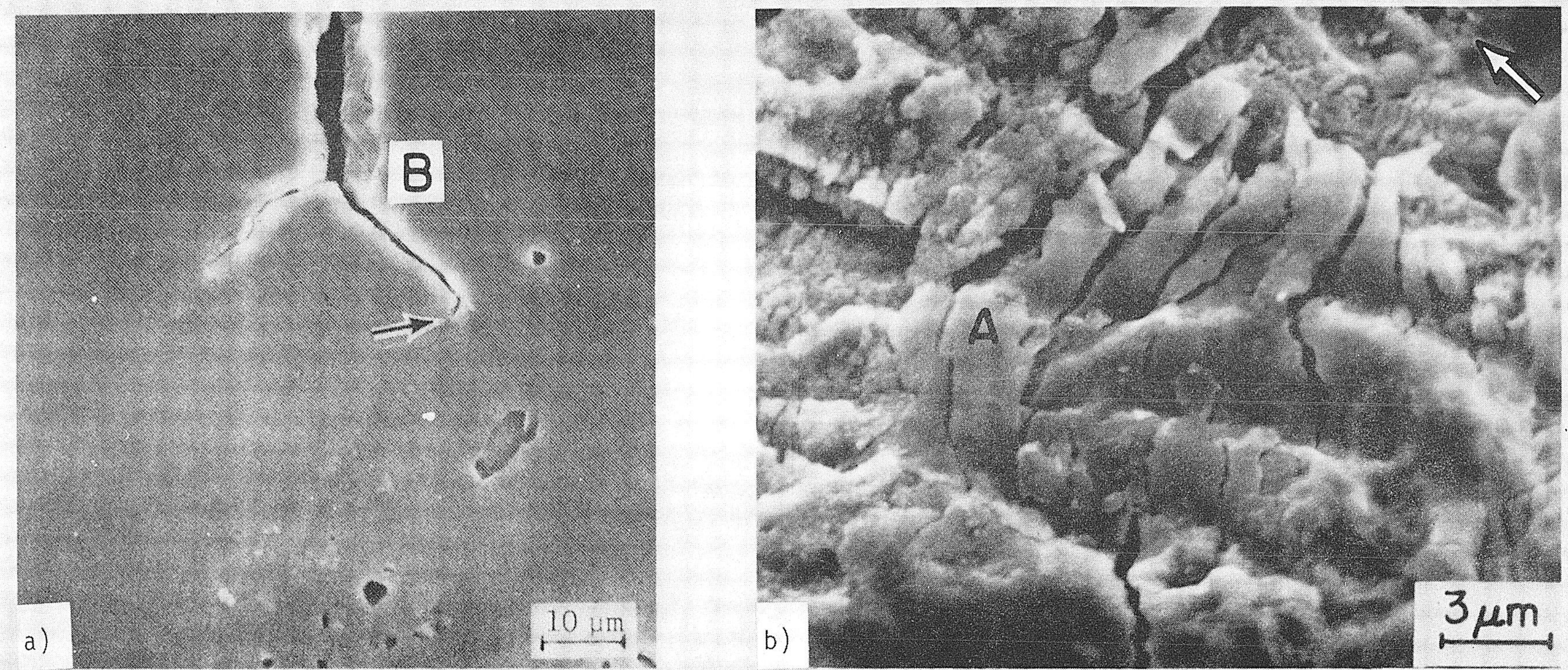

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Fig. 4: Fractography characteristic of Mode I fatigue crack growth following single overload cycles, showing a) crack branching (B) and blunting 160 cycles after the application of approximately a 100% overload in 6061-T6 aluminum alloy (6) and b) abrasion (A) and corrosion products formed during the rubbing between crack surfaces following a 100% overload in 2¼Cr-1Mo steel (5). Baseline conditions for both alloys were approximately $\Delta K = 10\ MPa\sqrt{m}$. Arrow in b) indicates general direction of crack growth.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720